UCRL- 101075
PREPRINT

RECOMMENDATIONS FOR A CRYOGENIC SYSTEM FOR ITER

Don S. Slack

This paper was prepared for submittal to
13th Symposium on Fusion Engineering
Knoxville, TN
October 2-6, 1989

September 20, 1989

RECOMMENDATIONS FOR A CRYOGENIC SYSTEM FOR ITER

Don S. Slack
Lawrence Livermore National Laboratory
University of California
P.O. Box 5511, L-643
Livermore, CA 94550

Abstract

The International Thermonuclear Experimental Reactor (ITER) is a new tokamak design project with joint participation from Japan, the European Community, the Soviet Union, and the United States. ITER will be a large machine requiring up to 100 kW of refrigeration at 4.5 K to cool its superconducting magnets. Unlike earlier fusion experiments, the ITER cryogenic system must handle pulse loads constituting a large percentage of the total load. These come from neutron heating during a fusion burn and from ac losses during ramping of current in the PF (poloidal field) coils. This paper presents a conceptual design for a cryogenic system that meets ITER requirements. It describes a system with the following features: a) Only time-proven components are used. b) The system obtains a high efficiency without use of cold pumps or other developmental components. c) High reliability is achieved by paralleling compressors and expanders and by using adequate isolation valving. d) The problem of load fluctuations is solved by a simple load-leveling device. e) The cryogenic system can be housed in a separate building located at a considerable distance from the ITER core, if desired. The paper also summarizes physical plant size, cost estimates, and means of handling vented helium during a magnet quench.

Introduction

Here we describe a cryogenic system suitable for ITER in its present form [1]. The purpose is to show that ITER requirements can be efficiently met by a relatively simple cryogenic system. Since the exact ITER capacity requirements are not defined yet, the cryogenic system parameters are given per 100 kW of 4.5 K refrigeration. Present estimates of ITER requirements are about 100 kW at 4.5 K. Larger or smaller capacity systems could be defined by scaling the flow rates and power requirements given here.

Basic System

The high cycle efficiency of this system is achieved in part by using an in-line turbine expanding helium from 2.0 to 1.0 MPa at about 6 K. Here helium properties are such that turbine inlet and outlet temperatures are the same. Consequently, the turbine does not introduce a temperature imbalance between adjacent heat exchangers. The cycle uses hardware (turbines, compressors, and heat exchangers) having easily attainable efficiencies. Consequently, a system of this design and performance could be built today with minimal development work.

Table I gives performance specifications for the 100 kW, 4.5 K refrigerator. The system uses the room-temperature compressors to force flow through the ITER coils and cases. Pressure to the coils can be as high as 1.0 MPa, and drop across the coils can be as high as 0.8 MPa, or any lessor values, by simple valve adjustments (adjustment of valves V3 and V5 in Fig. 1). The refrigerator cycle and cycle efficiency is not affected by coil pressure and pressure drop. Consequently, considerable flexibility is possible in designing the ITER coils, coil flow path areas, number of parallel paths, etc. The cycle is highly efficient, requiring 345 W of electrical input power per watt at 4.5 K. This includes power to supply the LN (liquid nitrogen) required for refrigerator operation. This point design provides 6.45 kg/s flow per 100 kW of system capacity to the ITER coils. However, by returning the flow to the dewar for recooling and returning it to the ITER coils a number of times, total flow can be increased to 13.0 or 19.0 kg/s.

The system uses presently available components, so values such as turbine and compressor efficiencies are those of proven equipment [2]. A complete thermodynamic and flow analysis was done. Resultant heat-exchanger, turbine, and compressor parameters are presented in Table II. An estimate of the refrigerator cold box size, based on the use of standard, brazed aluminum heat exchangers, is also given. Table III shows the flow and fluid properties throughout the refrigeration cycle. State point numbers correspond to those shown in Fig. 1.

Table I

Cryogenic System Specifications

Capacity (at 4.5 K)	as required (assume 100 kW for ITER)
Flow available to ITER core	6.45 kg/s per 100 kW capacity at 4.5 K or more (a)
Supply temperature	4.5 K
Supply pressure	1.0 MPa or less (b)
Return pressure	0.12 MPa or more (b)
Overall efficiency	342 W (electrical input) per W at 4.5 K (34.2 MW per 100 kW capacity) 309 W (elect. input) per W at 4.5 K, excluding power to generate liquid nitrogen for precooler

(a) The flow to the ITER core can be increased by several times the above 6.45 kg/s by using multiple passes, wherein each pass is returned to the dewar for recooling to 4.5 K.
(b) Supply and return pressure to the ITER core can be varied between 1.0 and 0.12 MPa by control of valves V3 and V5. This does not affect the cryogenic cycle or cycle efficiency since the refrigerator sees only the total pressure drop across V3, the ITER coils, and V5, and this is constant (1.0 MPa to 0.12 MPa). Alternately, if it is known that less than 0.88 MPa pressure drop is required by the ITER load, the above efficiencies can be improved by increasing the pressure drop across turbine 3.

Table II

Refrigerator Design—Hardware Parameters	
<u>Cold Box</u>	LN precool
	Three turbines
	Eight heat exchangers
	Approximate size—7-m dia. x 10-m high (assuming a single cold box for 100-kW cap.)
<u>Compressors</u>	
C1 flow	6.45 kg/s per 100 kW capacity
inlet temperature	300 K
inlet pressure	0.1 MPa
outlet pressure	0.3 MPa
compressor eff.	60 % isothermal
motor eff.	92 %
electrical input	7.78 MW per 100 kW capacity
C2 flow	10.64 kg/s per 100 kW capacity
inlet temperature	300 K
inlet pressure	0.3 MPa
outlet pressure	2.1 MPa (2 stages required)
compressor eff.	60 % isothermal
motor eff.	92 %
electrical input	23.06 MW per 100 kW capacity
<u>Turbines</u>	
T1 flow	2.65 kg/s per 100 kW capacity
inlet temperature	18 K
inlet pressure	2.0 MPa
outlet temperature	11 K
outlet pressure	0.3 MPa
power	77.8 kW per 100 kW capacity
efficiency	65 %
T2 flow	1.53 kg/s per 100 kW capacity
inlet temperature	40 K
inlet pressure	2.0 MPa
outlet temperature	27 K
outlet pressure	0.3 MPa
power	104 kW per 100 kW capacity
efficiency	61 %
T3 flow	6.45 kg/s per 100 kW capacity
inlet temperature	6 K
inlet pressure	2.0 MPa
outlet temperature	6 K
outlet pressure	1.0 MPa
power	25 kW per 100 kW capacity
efficiency	57%

<u>Heat Exchangers</u>

Number	LMTD (K)	UA (kW/K) (per 100 kW)	Q (kW) (per 100 kW)
1	0.32	122	39.1
2	1.18	108	128
3	1.33	66	87.7
4	1.5	166	249
5	1.5	357	536
	1.5	403	604
7	1.6	1411	2257
8	6.0	1984	11906
9	(LN precooler)		287

Approximate total heat exchanger volume per 100 kW capacity—46 m^2 (based on brazed aluminum exchangers)

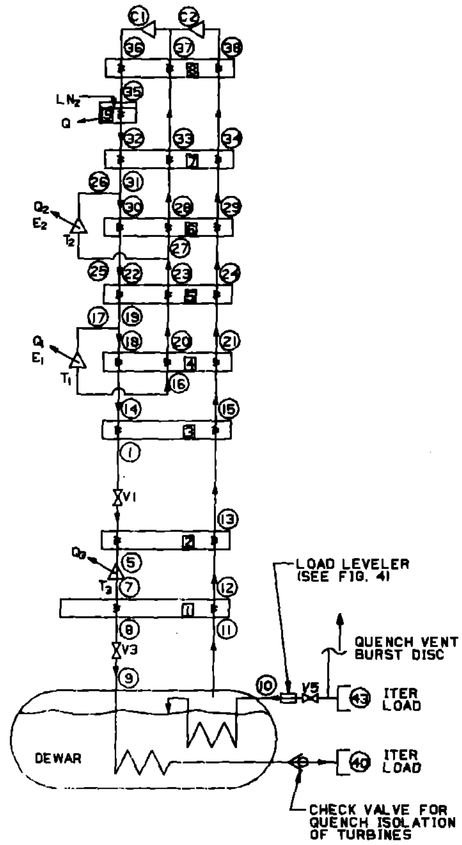

Figure 1. Schematic

Use of Cold Pumps in ITER

At first glance, it might appear system efficiency could be improved by using a separate, closed loop containing a cold pump to circulate helium to ITER. In this case, expanders in the refrigerator could utilize pressure drop previously required by the ITER load. This would result in a more efficient refrigerator. However, the cold pump requires shaft power, and this results in heat load to the cryogenic system. *It can be shown analytically that for any pressure drop across the ITER load and less than 100 % efficient cold pumps and expanders, heat load from the cold pump will always exceed the associated refrigerator gain.* Thus, the use of cold pumps will always result in a loss of overall system efficiency.

This, in addition to the developmental nature of cold pumps and the more limited pressure differentials available from cold pumps, makes them unattractive for ITER.

Nuclear Radiation Considerations

Figure 2 shows two helium loops going to the ITER core. One supports the magnets and the other provides warmer helium for thermal shielding purposes. Liquid nitrogen is not used in the ITER core because it can be activated by nuclear radiation.

Table III. Cycle State Points (Uses NBS 631)

State Point	Flow (per 100 kW) (kg/s)	Temp. (K)	Press. (MPa)	Enthalpy (J/g)
1	6.45	10	2.0	44.34
5	6.45	6	2.0	24.41
7	6.45	6	1.0	20.47
8	6.45	4.5	1.0	14.41
11	6.45	4.42	0.12	29.94
12	6.45	5.14	0.12	36.00
13	6.45	8.4	0.12	55.9
14	6.45	12	2.0	58.12
15	6.45	10.9	0.12	69.5
16	2.65	11.0	0.3	67.3
17	2.65	18.0	2.0	96.7
18	6.45	18.0	2.0	96.7
19	9.11	18.0	2.0	96.7
20	2.65	16.0	0.3	95.2
21	6.45	16.0	0.12	96.7
22	9.11	28	2.0	155.6
23	2.65	27	0.3	154
24	6.45	27.2	0.12	155.6
25	1.54	27	0.3	154
26	1.54	40	2.0	222
27	4.18	27	0.3	154
28	4.18	38	0.3	212
30	9.11	40	2.0	222
31	10.65	40	2.0	222
32	10.65	80	2.0	434
33	4.18	79	0.3	426
34	6.45	78.6	0.12	423
35	10.65	85	2.0	461
36	10.65	300	2.0	1579
37	4.18	293	0.3	1538
38	6.45	294.8	0.1	1546
40	6.45	4.5	1.00	14.41
43	6.45	4.42	0.12	29.94

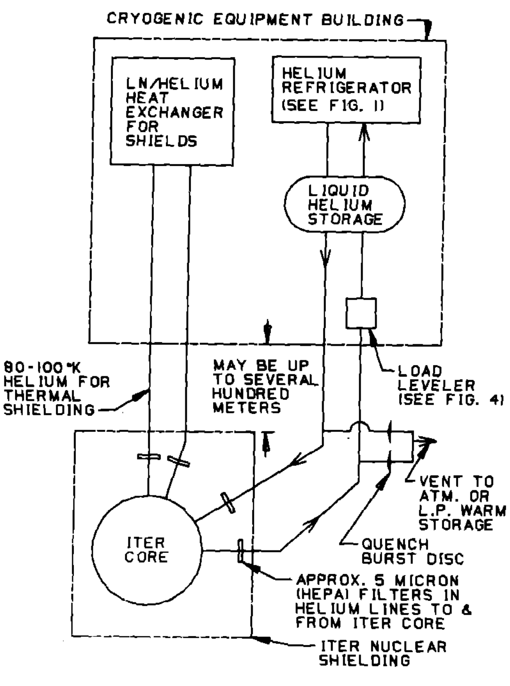

Figure 2. Layout

Although more study is needed, it appears that troublesome radiation will not be carried by the cryogen flows for the following reasons:

a) Helium itself does not activate.

b) Impurities (that might be activated) in the helium loops are extremely low because all other substances are frozen out in the low-temperature loop and high-purity helium from the low-temperature loop can be used to supply the 80 K loop.

c) Fine (5-micron, HEPA-type) filters can be used at the ITER shielding wall within the cryogenic piping to stop solid particulates.

d) No other mechanism exists whereby radiation could escape the ITER core via the cryogens.

Reliability Considerations for the ITER Cryogenic System

Figure 3 shows the basic cryogenic system presented above, but with more detail relating to the actual number of parallel components required because of the system size and for reliability considerations.

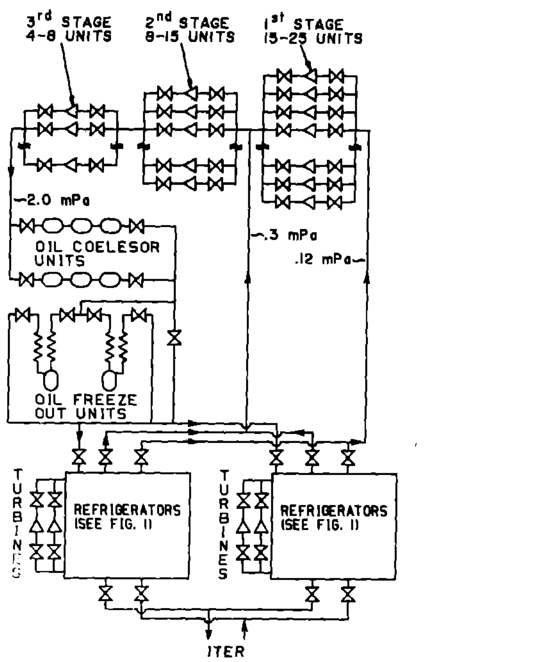

Figure 3. Use of parallel components for reliability

To enhance reliability, the system includes paralleled components with isolation valving such that failure of one component does not substantially reduce capacity or limit operation of the system. The failed component can be isolated, repaired, or replaced without affecting operation. Two identical cold boxes (refrigerator units containing heat exchangers, valving, and turbine expanders) are shown. The cold boxes are parallel connected to the compressor banks at the warm end and parallel connected to dewars and ITER loads at the cold end. Consequently, failure of a cold box (possibility from loss of vacuum or internal valve failure) will result in only partial reduction of system capacity.

In ITER, the majority of the cryogenic load exists only during burns when heating from neutron radiation and ac losses are present. Consequently, ITER can be operated in stand-by, with magnets at full field, and with considerably less than one-half of the cryogenic system capacity on line. This is the reason for using two or more identical components, each capable of being isolated and each plumbed to serve all of the ITER facility. In the event of a cold box failure, for example, ITER can be maintained in stand-by during repairs and testing can resume quickly.

Experience with other large operating systems has also shown the need of a paralleled oil-removal system. These are also shown in Fig. 3.

Load Fluctuations in ITER

ITER has highly fluctuating cryogenic loads. During burns, neutron and ac heating will cause sudden temperature changes in helium returning to the refrigerator [3–4].

Figure 1 shows a heat exchanger in the return line from ITER located within the large, helium-storage dewar. Its purpose is to prevent sudden temperature changes from reaching the refrigerator heat exchangers. However, more study is needed to determine if such a technique will adequately reduce disruptions to the refrigerator.

A simple, positive means of preventing serious refrigerator disruptions is shown in Fig. 4. Here, load on the refrigerator is held constant by an in-line electrical heater that compensates for ITER load changes. Response time of such a system would be amply fast, since heat capacities of solids, including the sensors and heater shown, are very low at these temperatures.

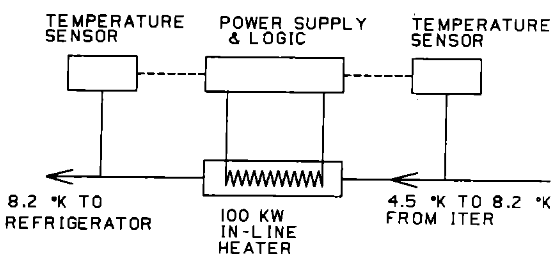

Figure 4. Load-leveling heater

Because of the simplicity and low cost of this heater system, it is recommended that it be installed as a back up to any other solutions to the load fluctuation problem.

ITER Cooldown Time

Cooldown time with the above system is substantially improved by the use of an auxiliary heat heat exchanger that uses liquid nitrogen to cool helium, which in turn cools the ITER cold mass to about 85 K. Such heat exchangers are simple and have proven successful in other large systems.[1] Cooldown time is relatively fast because a large refrigerator is required for ITER to handle neutron and ac heating and these loads do not exist during cooldown. Cooldown time based on present ITER parameters is:

From 300 K to 85 K	180 hours
From 85 K to 4.5 K	30 hours
Total Time	210 hours

Based on 9.8 Gg of ITER cold mass, use of a 1000-kW, auxiliary, liquid-nitrogen heat exchanger between 300 K and 85 K and a 100-kW refrigerator between 85 K and 4.5 K.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References

1. C. D. Henning and J. R. Miller, "Design Considerations for ITER Magnet System," Fusion Technology, vol. 15, No. 2, part 2B, pp. 915–921, 1989.

2. D. Slack et al., "Cryogenic Systems for the Mirror Fusion Test Facility," Advances in Cryogenic Engineering, vol 31, pp. 583–594, Aug. 1985.

3. D. Slack et al., "Cryogenic System Design for a Compact Tokamak Reactor," in Cryogenic Processes and Equipment, ASME publication, pp. 99–103, 1989.

4. J. Kerns et al., "Cryogenic Analysis of Forced-Cooled, Superconducting TF Magnets for Compact Tokamak Reactors," in Cryogenic Processes and Equipment, ASME publication, pp. 105–109, 1989.